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INTEGRATED IMAGING APPROACHES FOR EVALUATING LONG-TERM WEATHERING OF WOOD: A CASE STUDY OF FAÇADE ELEMENTS

INTEGRIRANI PRISTOPI, KI TEMELJIJO NA OSLIKOVANJU ZA VREDNOTENJE STARANJA LESA, IZPOSTAVLJENEGA VREMENSKIM VPLIVOM: ŠTUDIJA PRIMERA FASADNIH ELEMENTOV

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ABSTRACT

Wood is a widely used natural construction material, particularly in façade applications, where it is exposed to various abiotic and biotic degradation factors. This study investigates the effects of long-term weathering on a silver fir (Abies alba) façade element exposed outdoors for approximately 30 years under use class 3.1 conditions. The material had been treated with a copper–chromium-based preservative prior to installation and remained unmaintained during its service life. A comprehensive analytical approach was applied, including microscopy, density measurements, surface roughness analysis, contact angle determination, µXRF spectrometry, hyperspectral imaging, and FTIR spectroscopy. The results indicate that degradation was primarily limited to the outer 1–2 mm of the wood, where reduced density, increased roughness, and significant chemical changes were observed. Hyperspectral imaging enabled spatially resolved detection of chemical alterations, while µXRF revealed the redistribution and persistence of copper and chromium within the wood structure. No structural fungal decay was detected; however, surface colonisation by staining fungi was evident. The combined methodology proved highly effective for the non-destructive assessment of wood degradation and provides valuable insights into the long-term performance of treated wood in exterior applications.

Keywords: wood weathering, hyperspectral imaging, micro-XRF analysis, wood degradation, copper-based preservatives

IZVLEČEK

Les je široko uporabljen naravni gradbeni material, zlasti za fasade, kjer je izpostavljen različnim abiotskim in biotskim dejavnikom razkroja. Ta študija obravnava vplive dolgotrajnega staranja na fasadni element iz bele jelke (Abies alba), ki je bil približno 30 let izpostavljen zunanjim razmeram v pogojih razreda uporabe 3.1. Material je bil pred vgradnjo zaščiten s sredstvom na osnovi bakra in kroma in med uporabo ni bil dodatno vzdrževan. Uporabljen je bil celosten analitski pristop, ki je vključeval mikroskopijo, merjenje gostote, analizo hrapavosti površine, določanje kontaktnega kota, µXRF- spektrometrijo, hiperspektralno oslikovanje ter FTIR-spektroskopijo. Rezultati kažejo, da je bila razgradnja omejena predvsem na zunanji sloj lesa debeline 1–2 mm, kjer so bile zaznane zmanjšana gostota, povečana hrapavost in izrazite kemijske spremembe. Hiperspektralno oslikovanje je omogočilo prostorsko razločeno zaznavanje kemijskih sprememb, medtem ko je µXRF razkril prerazporeditev ter obstojnost bakra in kroma v strukturi lesa. Strukturnega glivnega razkroja ni bilo mogoče zaznati, vendar je bila opazna površinska kolonizacija z glivami modrivkami. Kombinirana metodologija se je izkazala kot zelo učinkovita za nedestruktivno oceno degradacije lesa ter ponuja pomemben vpogled v dolgoročno delovanje zaščitenega lesa v zunanjih razmerah.

Ključne besede: staranje lesa, hiperspektralno oslikovanje, µXRF-analiza, razkroj lesa, bakrovi zaščitni pripravki

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1 INTRODUCTION

1 UVOD

Wood is a natural, renewable material that has been widely used in construction for centuries due to its favourable mechanical properties, availability, and aesthetic appeal (Youngs and Hamza 2016; Humar et al. 2020). In contemporary architecture, wood remains an important material for both structural and non-structural applications, including façade cladding systems. Its relatively low density, ease of processing, and good strength-to-mass ratio make it particularly suitable for building applications. However, as a biological material, wood is inherently susceptible to degradation when exposed to environmental conditions (Reinprecht 2016).

In above-ground outdoor applications classified as use class 3 (European standard EN 335 2013), wood is installed above ground and exposed to weathering, but not in direct contact with soil or standing water. Under such conditions, the primary abiotic degradation factors include ultraviolet (UV) radiation, precipitation, and temperature fluctuations (Brischke and Thelandersson 2014). UV radiation leads to the photodegradation of lignin, resulting in surface discolouration, loss of cohesion, and the formation of a grey, fibrous layer (Cogulet et al. 2018; Alao et al. 2020). Rainwater contributes to the leaching of degradation products (e.g. quinones) and extractives, while repeated wetting–drying cycles promote microcracking and increased porosity (Keržič and Humar 2021; Keržič et al. 2021). Temperature oscillations further accelerate these processes by inducing dimensional changes that generate mechanical stresses and surface checking.

In addition to abiotic factors, wood in façade applications can be affected by biological agents. Among these, wood-decay fungi play a critical role, particularly under conditions where moisture content intermittently exceeds critical thresholds (Brischke et al. 2013; Kutnik et al. 2014; Alao et al. 2020). Brown rot fungi are especially relevant in such environments, as they preferentially degrade cellulose and hemicelluloses, leading to a rapid loss of mechanical strength while leaving modified lignin behind. This type of decay can significantly compromise the structural integrity of wooden elements if conditions become favourable for fungal growth (Green and Highley 1997; Clausen and Kartal 2003).

Apart from structural decay fungi, the wood surface is often colonised by staining microorganisms, commonly referred to as blue-stain fungi. The most prevalent species in outdoor conditions include *Aureobasidium pullulans* and *Sclerophoma pithyophila* (Gaur et al. 2010). These organisms do not substantially degrade the structural components of wood but form pigmented biofilms that lead to discolouration and reduced aesthetic quality. Their presence is typically associated with dust deposits on the surface, high humidity, and repeated wetting events, and they are often among the first colonisers of weathered wood surfaces (Schmidt 2006). Overall, the combined action of abiotic and biotic factors leads to the gradual deterioration of wood in exterior applications, affecting both its appearance and performance (Humar et al. 2020a).

The degradation of wood in exterior applications can be effectively slowed by biocidal treatments (Preston 2000). Among the most widely used are copper-based compounds, which provide broad-spectrum protection against fungal decay. Traditional preservatives based on copper–chromium formulations were extensively applied in the past due to their strong fixation and long-term efficacy. However, due to environmental and regulatory concerns, they have largely been replaced by copper–amine systems, which offer improved environmental compatibility while maintaining protective performance (Freeman and McIntyre 2008). In addition to biocidal treatments, surface coatings represent an important alternative or complementary approach. These coatings primarily function as water repellents, reducing moisture uptake and thereby limiting conditions favourable for biological degradation. However, unlike deeply penetrating preservatives, surface coatings are subject to weathering and require regular maintenance and reapplication to ensure long-term effectiveness (Petrič et al. 2007; Podgorski et al. 2019).

An understanding of weathering mechanisms is essential for developing effective protection strategies and improving the service life of wooden façade elements. This is the primary objective of this manuscript. In this study, we have utilised a novel methodology developed at the Department of Wood Science and Technology to demonstrate its applicability to weathering studies, namely hyperspectral imaging and μXRF microscopy. These two techniques provide complementary insights, enabling a more comprehensive assessment of material degradation. Hyperspectral imaging offers high-resolution, non-destructive mapping of chemical variations across the surface and subsurface layers by capturing detailed spectral information for each pixel. This allows the detection of subtle changes in wood polymers associated with weathering, such as lignin degradation and hemicellulose loss (Schimleck et al. 2023). In parallel, μXRF microscopy provides spatially resolved information on the distribution of inorganic elements, particularly preservative components such as copper and chromium compounds (Bartoll et al. 2003). The synergistic use of these methods enables the correlation of chemical degradation patterns with the redistribution and fixation of protective elements within the wood structure. This integrated approach significantly enhances the ability to distinguish between abiotic and biotic degradation mechanisms and to evaluate the effectiveness of preservative treatments over time. We believe that the combined methodology represents a powerful tool for advanced wood diagnostics, offering greater accuracy and depth of analysis than conventional techniques used in weathering studies. To the best of our knowledge, this is the first application of these imaging techniques to preservative-

treated, weathered wood, providing additional insight into the loss of active biocidal ingredients from treated wood during its service life.

2 METHODS
2 METODE

2.1 Material
2.1 Materiali

The investigated material consisted of a wooden façade element from the exterior cladding system of a single-storey building located on the hilly northern margins of the Dolenjska region (Mirna Valley area), near the Brunk Pass, Slovenia. The site lies in a transitional geographical zone between the Dolenjska and Štajerska regions, characterised by elevated terrain and greater exposure to environmental influences.

The façade element had been installed horizontally and used outdoors for approximately 30 years, based on information provided by the investor. During its service life, the material was continuously exposed to natural weathering factors, including solar radiation (UV), precipitation, temperature fluctuations, and atmospheric moisture. Based on the exposure, the conditions can be classified as use class 3.1 conditions (European standard EN 3352013). The investor informed us that, prior to installation, the wooden element was surface-treated with a biocidal preservative (Silvanol, Silvaprodukt), a copper- and chromium-based formulation commonly used in Europe at the end of the 20th century to protect against biological degradation (Richardson 1993; Pohleven 1998). No additional surface coatings or maintenance treatments were applied during the service period, and the element remained fully exposed to environmental conditions throughout its lifespan.

2.1 Methods
2.1 Metode

Samples from the wooden façade were cut into smaller specimens suitable for the respective analyses. Prior to analysis, the samples were conditioned under laboratory conditions (23 °C; 65% RH). Microscopic analysis, using mixed lighting comprising a combination of bright- and dark-field approaches, was performed using an Olympus DSX1000 digital microscope (Olympus, Tokyo, Japan). We analysed the surface of the selected samples and their cross-sections. Before microscopic analysis, the transverse xylotomic plane was aligned using a GSL 1 sliding microtome (Künten, Switzerland). Samples were immersed in cold water for 10 min prior to microtome sectioning, as described in previous research (Lesar et al. 2025).

The density of the wood was determined using a GeoPyc Envelope Density Analyzer (Micrometrics, Norcross, USA), which enables accurate volume measurement using a dry, free-flowing medium consisting of a mixture of small graphite and ceramic microspheres. The mass of each sample was determined before the measurement. The measurements were carried out on dry wood due to the technological requirements of the method (Arnič et al. 2021).

The surface of the samples was characterised using an Olympus LEXT OLS5000 laser scanning confocal microscope. First, 2D and 3D images of the weathered surfaces were recorded at 10× magnification. The measurement locations were selected randomly. The areal roughness was measured using Olympus software (OLS50-BSW). Several roughness parameters were calculated from the recorded surfaces. However, only the following representative parameter is presented. Sa, the most frequently used parameter, is the arithmetical mean height and represents the mean of the absolute ordinate values within a defined area (ISO 25178-2: 2012).

The sessile drop method, using a Theta optical tensiometer from Biolin Scientific Oy (Espoo, Finland), was employed to measure the contact angles of distilled water on the wood surface. These measurements were performed using the Young-Laplace add-in in OneAttension software, version 2.4. An optical goniometer equipped with a digital sensor captured the droplet shapes. Droplets of 4 µL were placed at three separate points on the weathered radial plane, conditioned at 23°C and 65% RH.

The elemental distribution of Cu and Cr in treated wood samples (surface and cross-section) was determined using micro-X-ray fluorescence (µXRF) spectrometry (Bruker, Tornado). Measurements were performed under reduced-pressure conditions (2000 Pa) to minimise X-ray absorption by air and improve signal stability. Prior to data acquisition, samples were conditioned under laboratory conditions and securely positioned on the instrument stage to ensure a flat, reproducible measurement geometry. Average XRF spectra were plotted for illustration.

The analysis was carried out using a single acquisition cycle with an X-ray tube power of 50 W and a tube current of 600 µA. The dwell time per measurement point was set to 14 ms, allowing rapid mapping of elemental signals while maintaining sufficient count statistics for quantitative comparison. Measurements were conducted in scanning mode, enabling the acquisition of spatially resolved elemental distribution maps across selected cross-sectional regions of the wood

specimens. Data acquisition yielded two-dimensional intensity maps corresponding to the characteristic fluorescence signals of the elements of interest, particularly copper and chromium compounds. The obtained spectral data were processed using the instrument's dedicated software environment. Initially, background correction and spectral deconvolution were performed to separate overlapping peaks and to compensate for matrix-related effects (Humar et al. 2025).

Although XRF imaging indicates the distribution of individual elements, hyperspectral imaging was used to characterise chemical changes in the wood. The acquisition was carried out using a ClydeHSI (Clydebank, UK) hyperspectral imaging system comprising an A3 translation stage, two tungsten-halogen reflectors for illumination, and a SWIR-384 (short-wave infrared) camera. The spectral range was 1000–2500 nm, with a spectral resolution of approximately 12 nm. The system uses a 2D sensor (384 spatial pixels × 288 spectral pixels) and, combined with the scanning setup, operates in push-broom mode. A 30 mm lens with an f/2.0 aperture was used, and the translation stage speed was set to automatic (40–50 mm/s). The acquisition procedure also included the collection of dark and white reference images before each measurement, accounting for illumination spectra, optical transmission, dark current, and the detector's quantum efficiency. A dark reference was obtained with the shutter closed, and a built-in white tile was used for the white reference. The obtained spectra were processed. Firstly, the first derivative was calculated, followed by principal component analysis (PCA). The mean spectra of three selected visually distinct areas corresponding to background pixels, non-weathered wood, and weathered wood, were extracted. They were used as references for spectral angle mapping (SAM) to better distinguish between the classes based on the angles between n-dimensional spectral vectors. An angle threshold of 0.15 radians was used for unsupervised classification. NIR spectra were also extracted to indicate differences between the various parts of the weathered wood. Finally, DRIFT spectra were recorded using a Spectrum Two FT-IR spectrometer (Perkin Elmer). The specimen was sampled at three locations using an abrasive silicon



Fig. 1: The cross-section of the wooden element indicates that the material is silver fir wood (*Abies alba*)

Slika 1: Prečni prerez lesenih elementov kaže, da je material izdelan iz lesa bele jelke (*Abies alba*)

carbide disc: (i) the frontal plane exposed to the elements, (ii) the reverse plane, which was in contact with the structure and thus not exposed to the elements, and (iii) the inner part of the plank. The spectra were recorded from 400 to 4000 cm^{-1} at 4 cm^{-1} intervals. The spectra were baseline corrected and normalised to the C-O-C band (1030–1050 cm^{-1}).

3 RESULTS
3 REZULTATI

The microscopic analysis of the cross-section indicates that the façade elements were made of silver fir (*Abies alba)* (Fig. 1). The cross-section of *Abies alba* is characterised by the absence of resin canals and a relatively uniform structure composed mainly of tracheids. Growth rings are clearly visible, with a distinct transition between earlywood (larger, thin-walled cells) and latewood (denser, thick-walled cells) (Wagenführ 2014). Silver fir is commonly used for wooden façades in Central Europe due to its wide availability and ease of processing (Klopčič et al. 2017). Although it has relatively low natural durability compared to some other species, it is often applied in exterior cladding when properly protected with coatings or preservatives. Its light colour and uniform texture make it aesthetically suitable for traditional and contemporary façade designs (Kang et al. 2017; Humar et al. 2020). On a scale where 1 indicates very durable wood and 5 indicates wood that is highly prone to fungal decay, silver fir wood is rated between 4 and 5 for durability (European standard EN 350 2016; Brischke et al. 2023).

The cross-section shows a rather rough surface, with small cracks radiating outward and following the parenchyma rays (Fig. 2). Both the surface and these cracks appear darker than non-weathered fir wood. The presence of five growth rings per 10 mm indicates the use of high-quality wood, as confirmed by its density. No evidence of fungal decay was observed in the wood cross-sections. The density of wood from the inner part, which was not exposed to weathering, was 370 kg/m^3, while the density of the outer weathered part was slightly lower (338 kg/m^3), indicating that some of the structural components had been leached from the wood. However, the density of the non-weathered part was slightly lower than the typical value reported in the literature (410 kg/m^3) but still within the reported range (320 to 710 kg/m^3) (Wagenführ 2014).

The wood surface shows significant degradation, with microscopic analysis identifying colonisation by wood-staining and mould fungi (Fig. 3). It is not possible to identify the observed clusters of spores to the species level. Based on literature data and morphological features, it is likely that the spores on the surface are asexual spores of *Aureobasidium* and *Sclerophoma pityophila.* Asexual spores of *Aureobasidium pullulans*, a common fungus found on weathered wood across Europe, were detected. Most discolouration of wooden façades is due to *Aureobasidium* and *Sclerophoma pityophila* (Gaur et al. 2010). These fungi mainly cause aesthetic issues without major structural damage but act as early colonisers that promote biodeterioration. Their persistence is due to high environmental tolerance, melanin production, biofilm formation, and efficient spore dispersal, enabling growth even with limited nutrients and brief moisture exposure (Schmidt 2006; Gostinčar et al. 2014). In addition to the spores, crystals are also present on the wood surface. The crystals are visible as white or bright spots. These crystals were not identified.

The façade element surface is highly roughened and strongly eroded due to long-term exposure to abiotic weathering factors, including UV radiation, rain, and temperature fluctuations (Fig. 4). These processes have preferentially degraded the earlywood, which is softer and less dense, while latewood is affected to a



Fig. 2: Cross-section of the analysed wood façade element

Slika 2: Prečni prerez analiziranega elementa lesene fasade

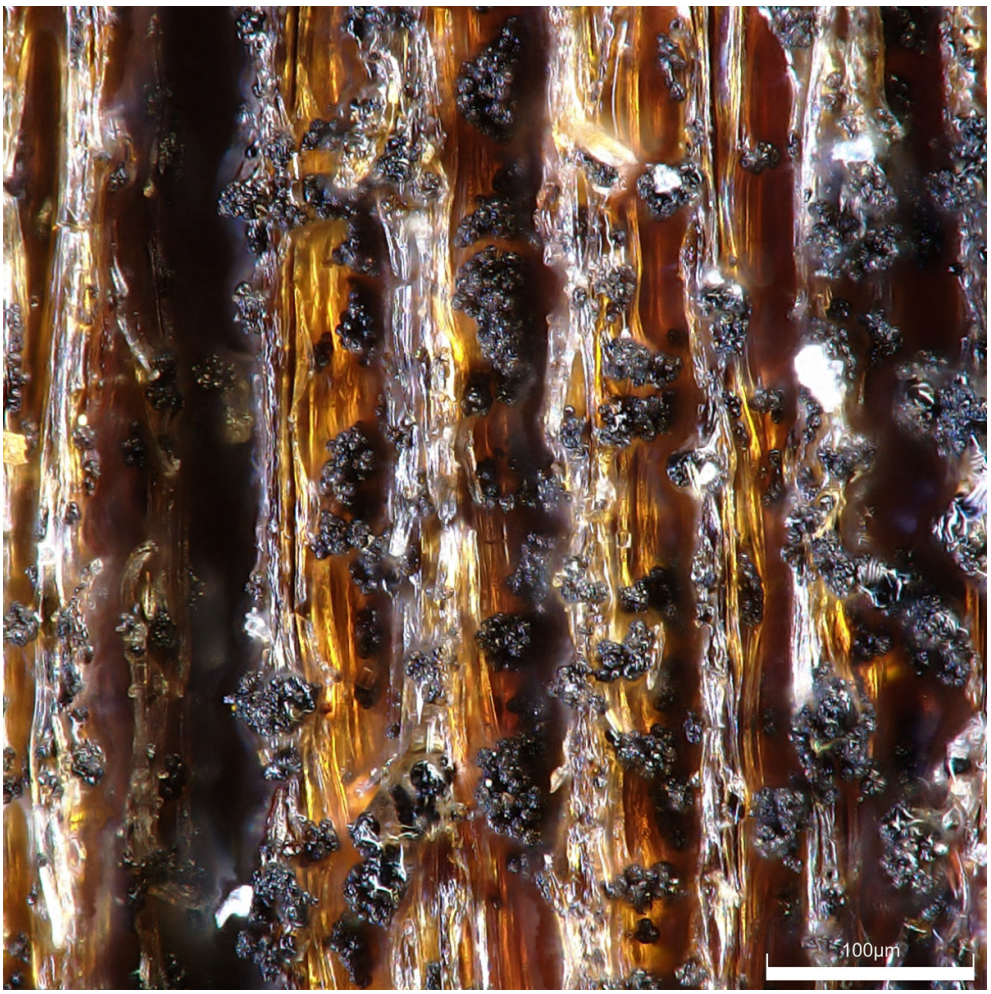


Fig. 3: Biofilm formation observed on the surface of the weathered wooden façade

Slika 3: Na površini vremensko postarane lesene fasade je opazna tvorba biofilma

lesser extent, resulting in a pronounced relief following the annual ring structure (approximately two growth rings within 10 mm). The measured roughness parameters confirm a highly developed surface: high values of $S_a \approx 375$ µm and $S_q \approx 410$ µm indicate significant average roughness, while $S_z \approx 1349$ µm (~1.35 mm) shows a large height difference between peaks and valleys. This corresponds well with the observed maximum height variation of about 1.2 mm, suggesting substantial material loss due to weathering. The near-zero skewness ($S_{sk} \approx 0$) indicates a relatively symmetrical distribution of peaks and valleys, whereas the low kurtosis ($S_{ku} \approx 1.42$) suggests a more flattened surface profile without sharp spikes. Additionally, the high developed interfacial area ratio (Sdr ≈ 76%) and slope (Sdq ≈ 2.47) reflect a highly textured and uneven surface (Csanády et al. 2015). Overall, the results clearly demonstrate that the wooden slat has undergone advanced surface degradation, with at least 1.2 mm of material removed, leading to increased roughness, higher surface area, and greater susceptibility to further weathering and biological colonisation.

The measured roughness values of the analysed façade element are considerably higher than those reported in the cited literature, which indicates a much more advanced stage of surface degradation. While the literature reports (Keržič and Humar 2021; Keržič et al. 2021) Sa values increasing from ~10 µm to ~50 µm after up to 27 months of natural weathering, the analysed sample shows Sa ≈ 375 µm, which is roughly 7–30 times higher. Similarly, the total height parameter (Sz ≈ 1349 µm ≈ 1.35 mm) confirms extreme surface erosion, far exceeding typical weathering-induced roughness reported in controlled studies (Fig. 5). This difference can be explained by the fact that the respective cited studies primarily consider relatively short-term exposure (months to a few years) and often controlled or semi-controlled conditions, whereas the analysed façade element was likely exposed to long-term outdoor conditions, including cumulative abiotic and biotic effects.

A weathered surface retains some hydrophobicity. The contact angle of water after 1 s on weathered wood is 109°, while a contact angle of 104° was determined on a non-weathered reference surface.

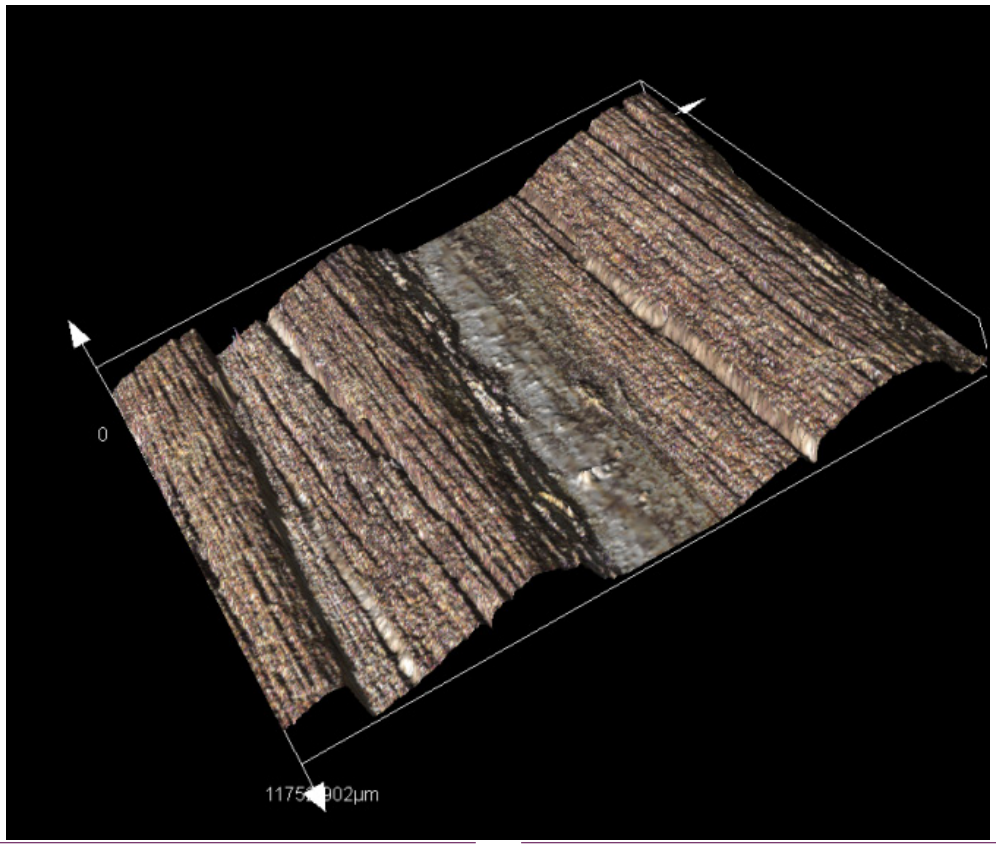


Fig. 4: 3D model of the wood surface after prolonged outdoor exposure

Slika 4: 3D model površine lesa po dolgotrajni izpostavitvi zunanjim razmeram

Contact angle analysis indicates that the water contact angle on the surface is approximately 110°. This value is slightly higher than that typically observed for untreated wood, where contact angles are generally lower. The increased contact angle suggests that the surface exhibits enhanced hydrophobicity. Consequently, the material is expected to absorb liquids less readily than freshly cut wood.

Wood treated with the classic CCB preservative (copper, chromium, and boron compounds) was analysed for retained active ingredients after weathering. XRF spectra (Fig. 6) showed significant levels of copper and chromium elements, with copper slightly more abundant, as expected for CCB-treated wood (Humar et al. 2021). Iron, chlorine, and sulphur were also found; iron likely came from corroded fasteners, while chlorine and sulphur were treatment residues (Lesar et al. 2016, 2018).

The main benefit of µXRF is its ability to reveal the spatial distribution of elements in wood, rather than

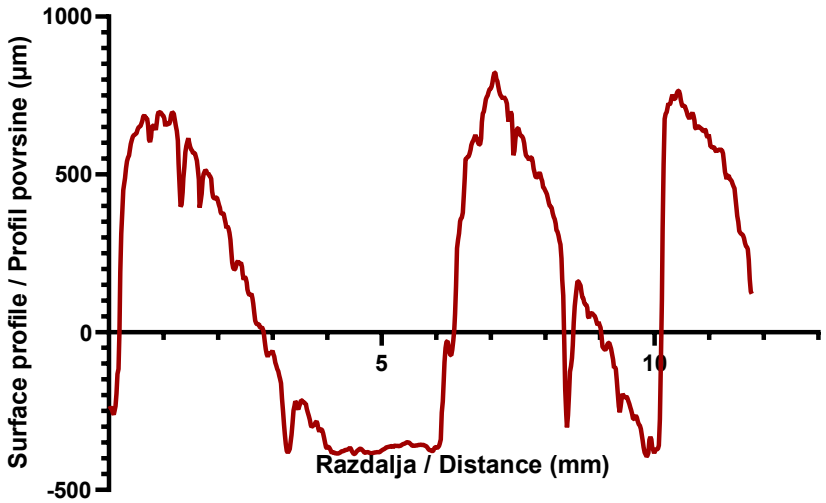


Fig. 5: 2D profile of the weathered wood surface

Slika 5: 2D profil površine staranega lesa

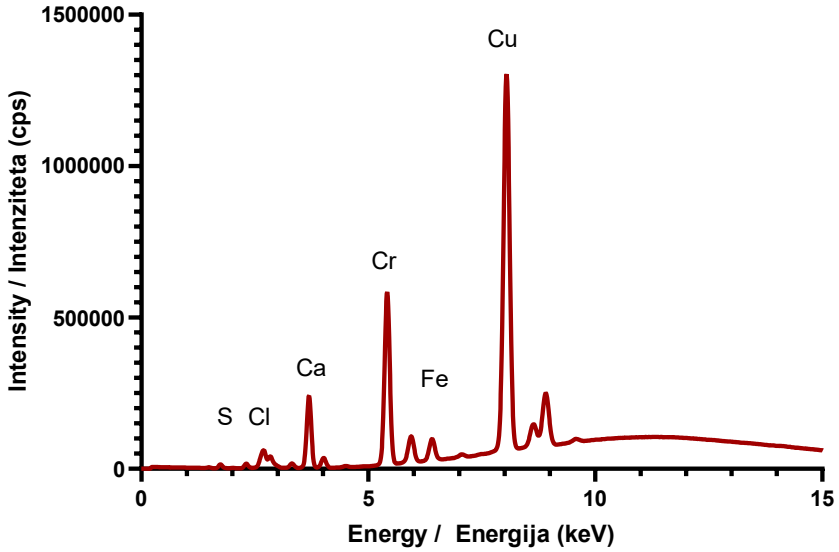


Fig. 6: Average XRF spectrum of the analysed wood

Slika 6: Povprečni XRF spekter analiziranega lesa

just their spectra. The distributions of copper and chromium were examined on both the surface and the cross-section of the façade elements. Their microdistribution correlates with weathering damage: earlywood, which erodes more, shows higher apparent concentrations of Cu and Cr, while latewood, being less degraded, also retains significant amounts of these elements, as observed in both surface and cross-sectional analyses (Fig. 7). The concentration of the analysed elements was higher at the surface than in the central part, which is consistent with findings that copper compounds are prone to redistribution and accumulation at the surface after impregnation due to mass flow and precipitation during drying. Such surface-enriched deposits are only weakly fixed and are therefore more susceptible to leaching during early exposure periods (Lupsea

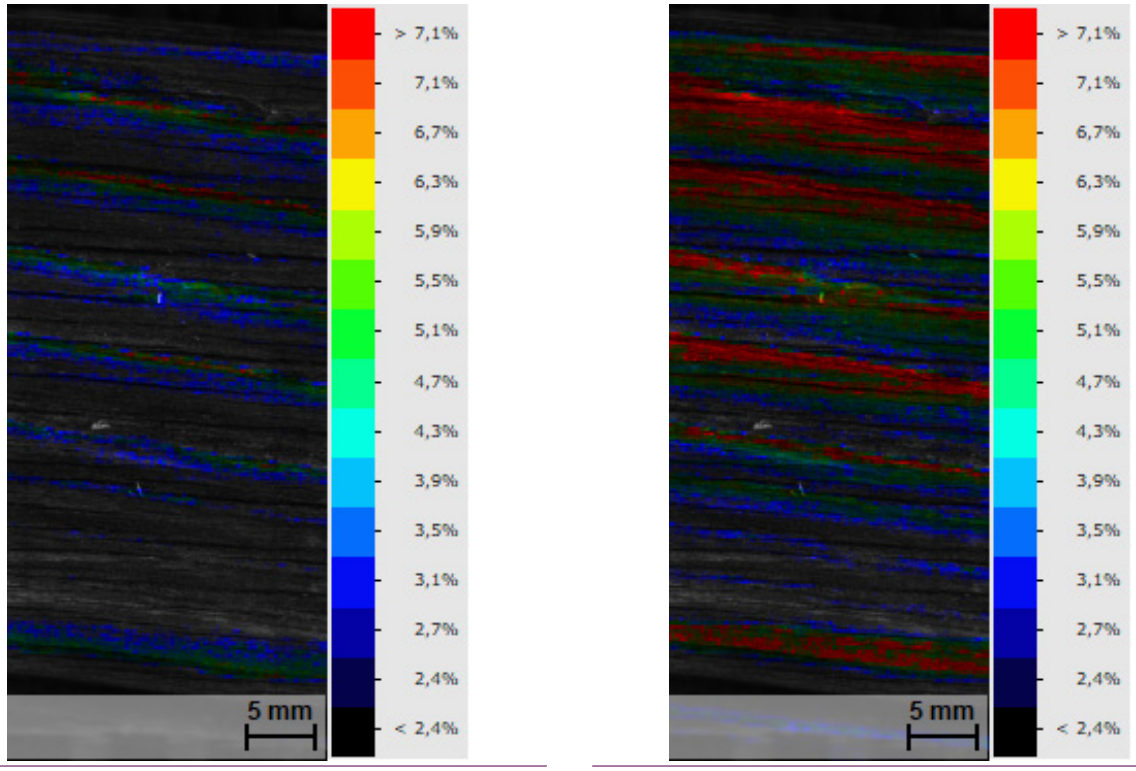


Fig. 7: Copper (left) and chromium (right) microdistribution on the surface of weathered wood. Regions indicated in red have higher concentrations than those marked in blue or black. Concentration values are provided for indicative purposes only.

Slika 7: Mikrorazporeditev bakra (levo) in kroma (desno) na površini postaranega lesa. Območja, označena z rdečo barvo, imajo višje koncentracije kot tista, označena z modro ali črno. Vrednosti koncentracij so podane zgolj informativno.

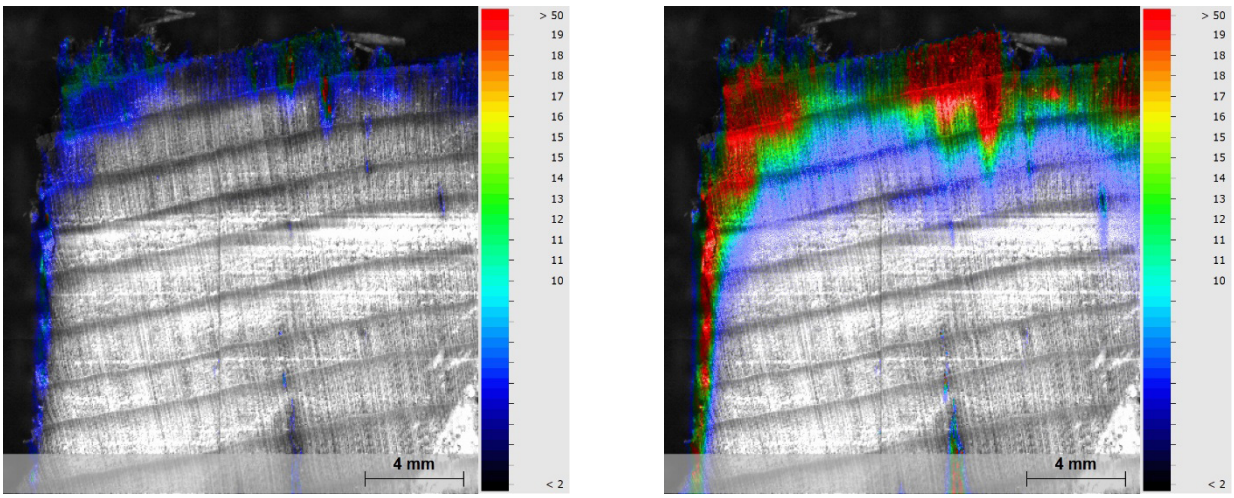


Fig. 8: Copper (left) and chromium (right) microdistribution in the cross-section of weathered wood. Regions indicated in red have higher concentrations than those marked in blue or black. Concentration values are provided for indicative purposes only.

Slika 8: Mikrorazporeditev bakra (levo) in kroma (desno) na preseku postaranega lesa. Območja, označena z rdečo barvo, imajo višje koncentracije kot tista, označena z modro ali črno. Vrednosti koncentracij so podane zgolj informativno.

et al. 2013).

Furthermore, the observed penetration of copper up to approximately 4 mm into the wood (Fig. 8) corresponds with literature data showing that most copper compounds remain in the wood even after prolonged exposure (over 80%), while a smaller fraction is gradually leached from the surface layers (Lebow 1996). Chromium, in contrast, exhibits significantly lower mobility due to its stronger fixation in the wood structure, which explains its more stable distribution in the outer layers, which were substantially eroded during weathering (Richardson 1993). The higher concentrations in degraded earlywood can also be attributed to preferential erosion of less dense tissue, combined with surface enrichment processes, rather than solely to deeper penetration. In addition, repeated wetting–drying cycles can enhance the migration of loosely bound copper toward the surface, further contributing to the observed distribution patterns.

The depth of wood degradation was assessed using hyperspectral imaging. Hyperspectral imaging is an advanced imaging technique that captures data across numerous narrow spectral bands, extending beyond the visible range into the infrared and/or ultraviolet regions of the electromagnetic spectrum. This approach enables the acquisition of a unique spectral "signature" for each pixel in the image, providing detailed information on the chemical composition and physi-

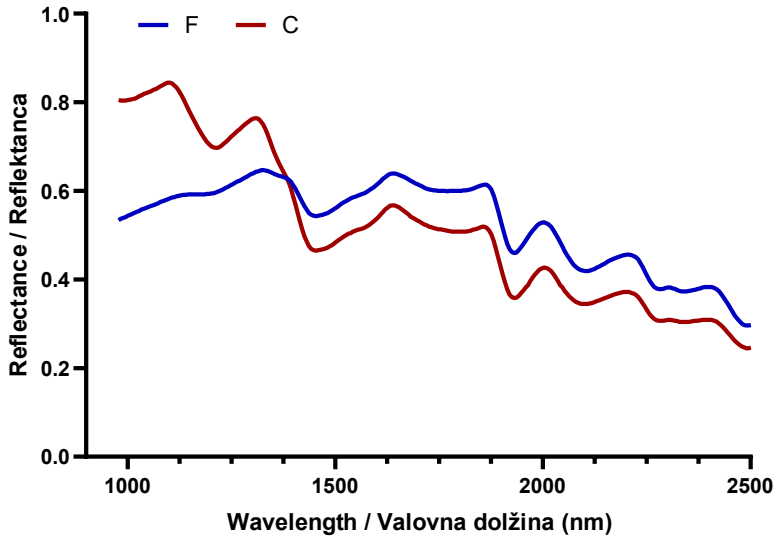


Fig. 9: NIR spectra of the reference, non-weathered wood (C), and the front weathered surface (F)

Slika 9: NIR-spektri referenčnega, neizpostavljenega lesa (C) in sprednje vremenu izpostavljene površine (F)

cochemical properties of the material (Smeland et al. 2016; Schimleck et al. 2023).

In the context of wood analysis, hyperspectral imaging allows for the detection and spatial mapping of degradation processes, including chemical alterations associated with fungal decay, weathering, or other deterioration mechanisms. Unlike conventional imaging methods, which rely solely on visual information, hyperspectral data can reveal subtle changes in material composition that are not discernible to the naked eye. This makes it particularly suitable for assessing the depth and extent of damage in wood, as variations in spectral response can be correlated with different stages or intensities of degradation (Schimleck et al. 2023).

The NIR spectra exhibit noticeable differences in overall intensity and band definition, with the non-weathered wood spectrum (C) showing consistently higher absorbance than the weathered surface spectrum (F). Characteristic absorption bands associated with O–H and C–H groups are less pronounced and broader in the weathered spectrum, indicating chemical alterations in wood polymers. In addition, the weathered spectrum displays a general smoothing of spectral features, suggesting degradation of hemicelluloses and modifications to the lignin structure (Fig. 9). These changes are consistent with increased weathering and reduced structural integrity in the corresponding wood sample (Bächle et al. 2012).

Hyperspectral imaging analysis revealed that the degradation is primarily confined to the outermost 1–2 mm of the wood surface (Fig. 10). This superficial layer exhibits distinct spectral characteristics compared with the underlying material, indicating alterations in its chemical composition associated with weathering processes. In addition, the density of this outer layer is reduced relative to the inner, less affected wood. This decrease in density can be attributed to the combined effects of environmental exposure, including moisture fluctuations, ultraviolet radiation, and temperature variations, which promote the degradation of structural polymers such as cellulose and hemicelluloses (Cogulet et al. 2018). These processes lead to material loss, increased porosity, and a consequent reduction in mechanical integrity. The findings indicate that the observed deterioration is largely limited to the surface, with the bulk of the material remaining comparatively intact. This spatially resolved information highlights the usefulness of hyperspectral imaging as a non-destructive tool for assessing both the extent and depth of wood degradation.

The IR spectra show significant differences be-

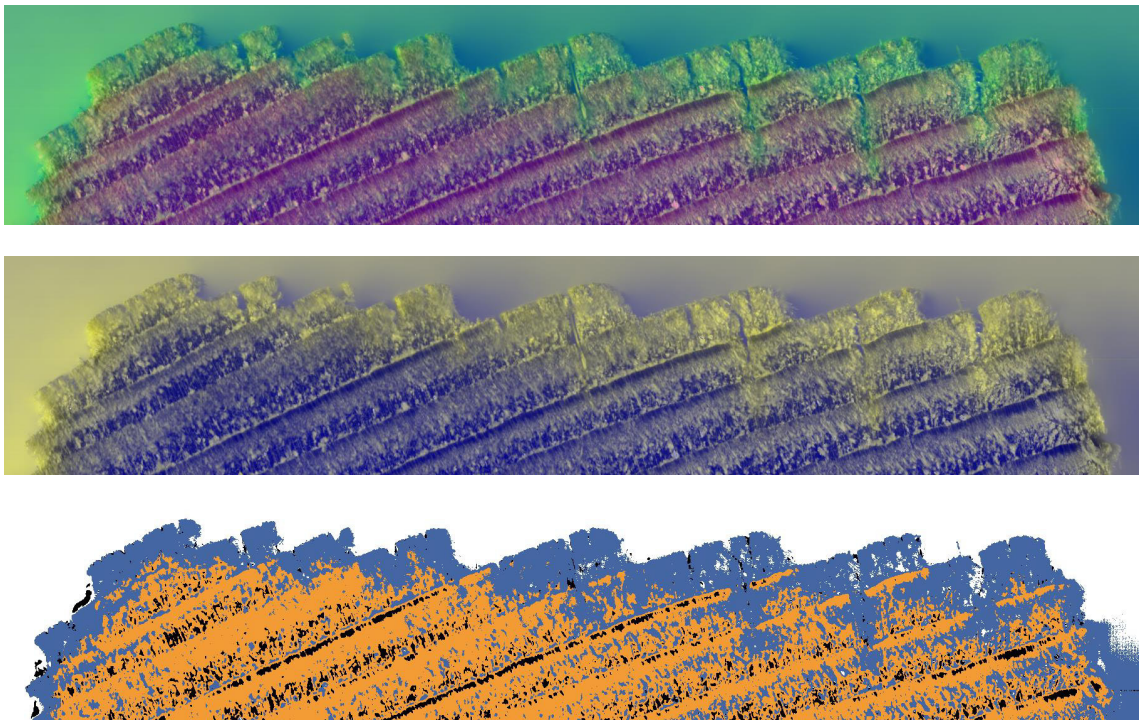


Fig. 10: Results of hyperspectral imaging of the weathered surface. Two RGB images based on the first three PCA components (top) are presented along with an image based on SAM (bottom), where white represents the background, blue represents weathered wood, orange represents non-weathered wood, and black represents unassigned pixels.

Slika 10: Rezultati hiperspektralnega oslikovanja. Prikazani sta dve RGB-sliki na osnovi prvih treh komponent PCA (zgoraj) in slika na osnovi SAM (spodaj), kjer bela ponazarja ozadje, modra izpostavljeni les, oranžna neizpostavljeni les in črna nedodeljene slikovne točke.

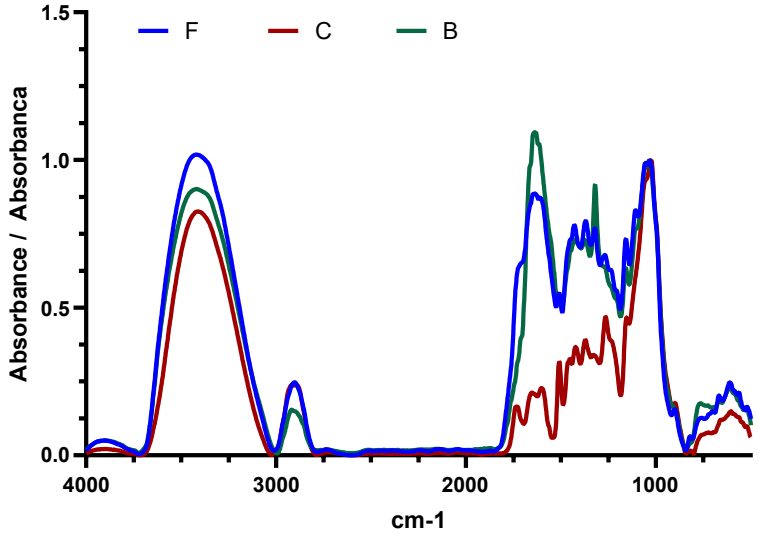


Fig. 11: FTIR spectra of the reference, non-weathered wood (C), the back side of the façade elements (B) and the front weathered surface (F)

Slika 11: FTIR-spektri referenčnega, ne-izpostavljenega lesa (C), zadnje strani fasadnih elementov (B) in sprednje, vremenu izpostavljene površine (F)

tween the sample surfaces. These differences are primarily influenced by the presence of the biocide. Based on the data obtained by μXRF, we know that a copper-chromium biocide was used to treat the surface of this sample. The spectrum of the cross-section shows several characteristic bands expected in native silver fir (Fig. 11). The bands at 3400 cm^{-1} and 2950 cm^{-1} are characteristic of O–H and C–H bonds, respectively, which are abundant in both untreated and treated wood. The major differences occur between 1800 and 1000 cm^{-1}. The inner part of the plank, which was not exposed to either the biocide or weathering factors, exhibits the typical chemical structure of wood with a C=O hemicellulose band at 1735 cm^{-1} and several lignin-related bands at 1650 cm^{-1} (Aromatic C=C), 1600 cm^{-1} (Aromatic C=C), 1506 cm^{-1} (Aromatic (C=C), 1452 cm^{-1} (Lignin C–H), 1420 cm^{-1} (Aromatic C=C), and 1370 cm^{-1} (Lignin C–H), and 1260 cm^{-1} (Lignin C–O) (Ganne-Chédeville et al. 2012). The spectra of the biocide-treated surfaces exhibit major differences, especially at 1650 cm^{-1}, where the band shifts to 1635cm^{-1}, with a significant increase in intensity on both treated surfaces, compared with the inner part of the plank, into which the biocide did not penetrate. The change in the 1650 cm^{-1} band is due to the complexation of hexavalent chromium in the biocide and its subsequent reduction to stable and less toxic trivalent chromium due to the reducing potential of lignin (Lin and Wang 2016). The FTIR results support the conclusion that a copper-chromium-based biocide was used as a surface treatment for the protection of this sample.

4 CONCLUSIONS
4 ZAKLJUČKI

The investigated silver fir (*Abies alba*) façade element, exposed to outdoor conditions for approximately 30 years, exhibited pronounced surface degradation primarily driven by long-term abiotic weathering, while the inner structure remained largely intact. Microscopic, density, and hyperspectral analyses consistently indicated that deterioration was confined mainly to the outer 1–2 mm, where reduced density, increased porosity, and significant chemical alterations were observed. Surface roughness measurements revealed extreme erosion, far exceeding values reported in short-term studies and highlighting the cumulative impact of prolonged natural exposure under use class 3.1 conditions. Elemental analysis confirmed the persistence and redistribution of copper- and chromium-based preservatives, with higher concentrations detected in the surface layers and preferential accumulation in degraded earlywood. Despite biological colonisation by staining fungi and the formation of biofilms, no structural fungal decay was identified, suggesting that the preservative treatment remained partially effective in preventing deeper biodeterioration.

5 SUMMARY
5 POVZETEK

Les je naraven, obnovljiv material, ki se zaradi dobrih mehanskih lastnosti, estetskega videza in dostopnosti pogosto uporablja v gradbeništvu, zlasti pri fasadnih oblogah. V zunanjih razmerah, ki ustrezajo ra-

zredu uporabe 3.1, je les izpostavljen številnim abiotskim dejavnikom, kot so UV-sevanje, padavine ter temperaturna nihanja, ki povzročajo postopno razgradnjo površinskih slojev. Poleg tega lahko na les vplivajo tudi biotski dejavniki, predvsem glive razkrojevalke lesa, med katerimi imajo pomembno vlogo glive rjave trohnobe, ter glive modrivke, kot sta *Aureobasidium pullulans* in *Sclerophoma pithyophila*, ki vplivajo predvsem na estetski videz materiala. Za upočasnitev razgradnih procesov se uporabljajo zaščitni sistemi, kot so bakrovi biocidni pripravki in površinski premazi, katerih učinkovitost je odvisna od pravilne uporabe in vzdrževanja.

V raziskavi smo analizirali leseni fasadni element iz bele jelke (*Abies alba*), ki je bil približno 30 let izpostavljen zunanjim vplivom brez dodatnega vzdrževanja. Material je bil pred vgradnjo zaščiten z bakrovo-kromovim sredstvom CCB. Za celostno karakterizacijo degradacije smo uporabili kombinacijo sodobnih analiznih metod, vključno z mikroskopijo, merjenjem gostote, določanjem hrapavosti površine, merjenjem kontaktnega kota, μXRF- spektroskopijo, hiperspektralnim oslikovanjem ter FTIR-spektroskopijo. Poseben poudarek je bil na uporabi inovativne metodologije, ki združuje hiperspektralno oslikovanje in μXRF-analizo, saj omogoča prostorsko razločeno spremljanje kemijskih sprememb in porazdelitve elementov v lesu.

Rezultati so pokazali, da je degradacija omejena predvsem na zunanji sloj lesa debeline približno 1–2 mm, kjer je prišlo do zmanjšanja gostote, povečane poroznosti in izrazitih sprememb v kemijski sestavi. Površina lesa je bila močno erodirana, kar potrjujejo visoke vrednosti hrapavosti, ki bistveno presegajo vrednosti iz literature za kratkotrajno izpostavljenost. Mikroskopska analiza ni pokazala strukturnega glivnega razkroja, vendar je bila zaznana kolonizacija površine z glivami obarvanja, ki tvorijo biofilm.

Analiza z μXRF je pokazala, da sta baker in krom še vedno na v lesu, pri čemer je njuna koncentracija višja v površinskih slojih, kar je posledica prerazporeditve med procesi vlaženja in sušenja. Hiperspektralno oslikovanje je omogočilo natančno določitev globine degradacije ter razlikovanje med nepoškodovanim in poškodovanim materialom. FTIR-analiza je dodatno potrdila kemijske spremembe, povezane tako z vremenskim staranjem kot z interakcijo lesa z zaščitnim sredstvom.

Rezultati raziskave potrjujejo, da je kombinacija hiperspektralnega oslikovanja in μXRF-analize zmogljivo in nedestruktivno orodje za preučevanje degradacije lesa. Takšen pristop omogoča boljše razumevanje procesov staranja in učinkovitosti zaščitnih sistemov ter prispeva k razvoju trajnejših rešitev za uporabo lesa v zunanjih razmerah.

DATA AVAILABILITY
DOSTOPNOST RAZISKOVALNIH PODATKOV

All research data presented in this study were generated by the authors as part of this research. The datasets are available from the corresponding author upon reasonable request.

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